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To cite this article: Araz Ardehali Barani *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **604** 012063

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Clean, flawless and thinner stainless steel valves by strip casting

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Abstract. Compressor valves are made of hardened and tempered martensitic stainless steels. They were first produced from ingot cast material. Later continuous casting technology largely replaced this process, which led to improved, more uniform, properties and higher yields in the production of hot strip. A further development was made around the turn of the millennium, when strip casting was first used for the production of stainless steel strip, directly from the melt. In this paper the steel grade *Zapp 1.4028MO* produced via both production routes: a) Continuous casting - hot rolling - cold rolling and b) Strip casting - cold rolling, are compared with respect to their microstructure evolution and static/dynamic mechanical properties. It is shown that strip cast material can not only substitute that of the traditional continuous casting route, but moreover deliver performance advantages with thin stainless steel valves used within air conditioning units and household refrigerators.

1. Introduction

The material used for valves in compressors must fulfill a number of requirements [1, 2]. Of utmost importance is the endurance limit of the material. This determines whether the valve lasts for the entire life of the compressor. It is known that a combination of high tensile strength and high toughness results in good fatigue performance of steel [3, 4]. Furthermore, it has been shown, that the aforementioned properties can be tailored by microstructure optimization [5]. In addition, the absence of hard and brittle non-metallic phases is beneficial for an extended lifetime of metallic components under dynamic loading [6]. Non-metallic inclusions and larger carbides can be sources of crack initiation, leading to component failure. Therefore, material with a higher level of cleanness, i.e. fewer and/or smaller inclusions and carbides, could increase the lifetime and endurance limit of materials or components [6].

Besides the material properties of valve steel, the geometric features of the semi-finished products used to produce valves are relevant for their function. Any deviation of the steel strip geometry from the ideal flat shape can result in valve leakage during operation, as the valve may not completely seal the discharge port. The shape and flatness of the cold rolled strip used to make valves depend on the thickness profile and cross sectional shape of the semi-finished material used for its production. The thickness profile, defined as the variation of the thickness over the width, also known as the crown, is dependent on the material cross section prior to hot rolling to strip as well as the hot rolling machinery used. The thickness profile becomes increasingly important as the thickness of the steel strip becomes thinner. During the subsequent cold rolling process tight thickness tolerances, along the width of the strip, can only be obtained if the crown or thickness profile of the incoming hot strip is also suitably tight.



Therefore to ensure superior, uniform material properties, as well as tight geometrical tolerances at thinner gauges, the cleanness and thickness profile of the starting steel strip must be carefully controlled. As the strip casting technology can improve both of these features [7-11], it was considered an attractive alternative for the production of flapper valve material. In this paper, the use of this novel casting technology for the production of thin precision strip used for valve applications is investigated for the first time.

1.1. Casting technologies for stainless steel strip

Currently, all stainless strip used as semi-finished product for flapper valves is produced by either ingot or continuous slab casting. These two traditional casting technologies exhibit different metallurgical characteristics that determine both the cleanness and uniformity of the material microstructure. Until the late 1970s ingot casting was the only industrial method used for the production of starting material, solid blocks, for stainless steel strip manufacture. Continuous casting was developed in the 1970s, as a casting technique for the production of wider stainless steel strip. In the 1980s the process was commercialized for the production of wide martensitic stainless strip. The change of casting method, from ingot casting to continuous casting of slabs, not only led to an increase in yield but also, with respect to quality, a higher uniformity of slab material produced from single or multiple melts.

Strip casting was invented as far back as 1857 by Sir Henry Bessemer, for the production of metals [8]. However, the twin-roll casting method as described by Bessemer was not used for the industrial production of stainless steel until the 1990s. Martensitic stainless steels were first produced using this casting technique after the turn of the millennium. The method offers high solidification rates and metallurgical advantages compared to the more established casting processes.

Figure 1 shows typical casting piece thicknesses and cooling rates produced in continuous slab casting and strip casting. Typical casting parameters for stainless steel are presented in table 1. Compared to the two conventional casting methods, the very low solidification time observed in strip casting leads to small dendrite arm spacing, small primary carbides (if any at all) within martensitic stainless steels and smaller non-metallic inclusions. In summary, the high solidification rate results in a refined cast microstructure for martensitic stainless steels.

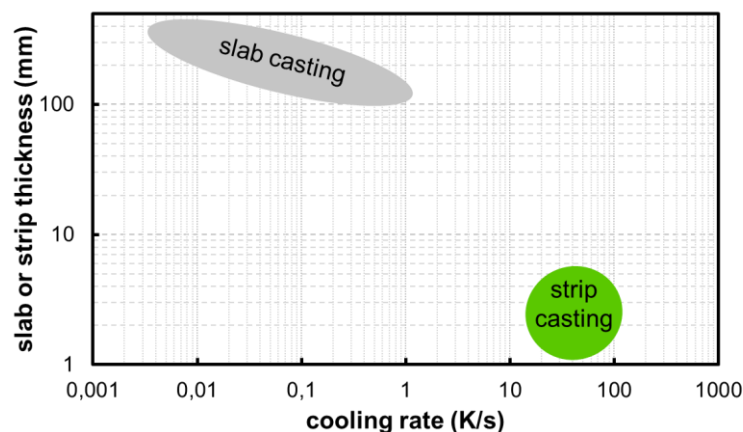


Figure 1 - Comparison of cooling rates observed in continuous slab casting and direct strip casting from the melt

Table 1 - Typical casting characteristics for the various routes

	ingot casting	continuous thick slab casting	twin-roll strip casting
thickness (mm)	>300mm	150 to 300	1.5 to 5
casting speed (m/min)	-	0.8 to 2	50 to 150
solidification time (s)	103 to 105	103	<0.5
cooling rate (K/min)	0.1 to 5	0.3 to 10	500 to 1000

The refined microstructure arising from the strip casting process can only be compared with the those of the two conventional routes once in the hot or cold rolled condition and at a similar thickness. In the conventional routes, the refinement of the microstructure takes place during the reheating and forming of the ingot and slab by recrystallization and diffusion processes.

1.2. Conventional production of strip by hot rolling

Strip casting can produce strip of 1 to 5 mm in thickness. Compared to the conventional process routes the thin strip gauge is achieved directly upon casting. Therefore, significantly less energy is consumed as the subsequent reheating and hot forming processes are no longer required. The strip casting method has further advantages compared with the conventional routes. During the hot rolling of large, semi-finished cross sections to final hot strip thicknesses, machine work roll bending results in a thickness difference between the center and edges of the strip. The resulting crown is a typical feature with hot rolled strip produced from the re-rolling of slabs or ingots. This inherent thickness profile cannot be fully removed during the subsequent cold rolling process. However, minimizing these thickness differences is essential in achieving thin precision strip with very tight thickness tolerances, whilst at the same time fulfilling the tight flatness requirements required for the production of valve material.

A further consideration is that during hot rolling processes the surface of the slab, semi-finished transfer bar or strip can incur surface defects by chemical reactions or mechanical damage. Contrary to steels with a lower chromium content, scale formation is not as pronounced with stainless steels and thus any defects present on the surface remain through production. Any material exhibiting such surface defects, caused either during the reheating of slabs or the subsequent hot rolling processes, must be diverted or scrapped. Such cases ultimately lead, therefore, to increased yield loss. Due to the avoidance of reheating and forming steps with the strip casting method, it is therefore reasonable to assume that this route can ultimately produce strip with a reduced frequency of surface defects and thus to an improved surface quality.

1.3. Motivation

The intention of this work is to assess the suitability of the strip casting process for the production of thin martensitic stainless steel strip used to manufacture valves used in highly demanding compressors.

2. Experimental

In this study, strip samples of steel grade *Zapp 1.4028MO* (similar to X38CrMo14) produced via the conventional and strip casting route were analyzed. The typical chemical composition of this steel grade is given in table 2. The conventional route consists of continuous casting to slab, hot rolling to strip, hot strip annealing and pickling and cold rolling to final thickness with intermediate and final annealing stages. The starting thickness of the annealed cold rolled strip, used in this study, was 1.0mm.

Table 2 - Chemical composition of the strips used for the investigation
(*Zapp 1.4028MO*, comparable to X38CrMo14)

	C	Si	Mn	Cr	Mo
content in weight percent	0.38	0.38	0.37	13.20	1.0

The cast strip sample set was produced via a twin-roll strip caster and a low hot-deformation stage to a thickness of 2.5mm, immediately after casting. The coil produced was subsequently annealed and pickled. Figure 2 illustrates the process flow for both the conventional continuous cast and strip cast route.

The strip microstructure, thickness profile, surface quality and mechanical properties resulting from both routes were compared. Both sets of strip were cold rolled to the final thickness of 0.15mm on a 20-roll Sendzimir mill. Intermediate annealing was carried out on a continuous annealing line under a hydrogen atmosphere. The final reduction of the material thickness, and the parameters used in the final hardening and tempering process, were identical. All heat treatment parameters corresponded to the standards used at Zapp Precision Metals for the production of quenched and tempered *Zapp 1.4028MO*. The final hardening and tempering treatment was carried out in a continuous hardening furnace, again under a hydrogen atmosphere.

V2A etchant consisting of 100 ml hydrochloric acid, 100 ml water and 10 ml nitric acid was used to prepare material samples, prior to the light and scanning electron microscopy, used to investigate the secondary carbide size and distribution. Electron back-scatter diffraction was used to investigate the martensite microstructure of both sample sets. Samples in the rolling direction were prepared using standard grinding and polishing procedures. An area of 60µm x 60µm was mapped, with a step size of 50nm.

The tensile properties were determined in the longitudinal direction, according to standard practice, from 10 samples taken from both ends of the heat treated strip coils. Cyclic fatigue in bending was measured using a three point bend test. Again, testing was performed in the longitudinal direction. The stress ratio *R* used was 0.1 and the test frequency was 10 Hertz. Test runs were stopped if the samples exceeded two million cycles.

3. Comparison of material received from the conventional and strip casting routes

3.1. Non-metallic inclusions

The main difference between continuous casting and strip casting is the dwell time of the melt after entry into the mould (in continuous casting), or the pool between the casting drums (in strip casting). The metallurgy prior to the casting process will be the same if produced in the same melt-shop, as the practices used to purify the metal from non-metallic phases will be consistent. Thus, the main difference between the two routes is the material solidification rate. This determines the time available for oxides in the melt to coagulate. Furthermore, the flow conditions prior to full solidification differ between the two casting processes. Cold rolled strip from the conventional route exhibits non-metallic inclusions up to several hundred micrometers. Whereas material produced via strip casting exhibits a maximum inclusion size significantly below 100 micrometer.

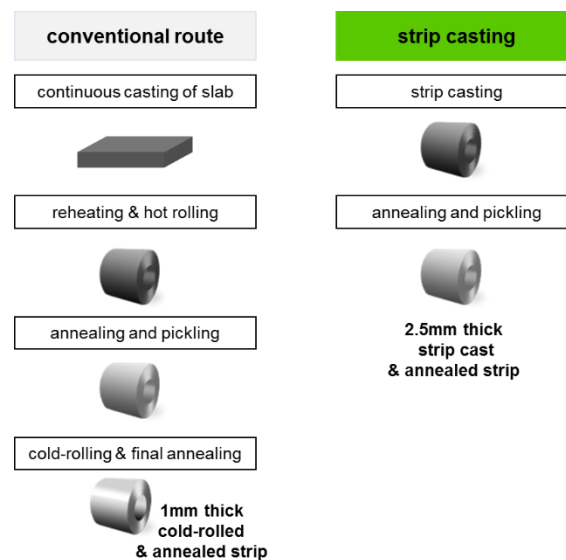


Figure 2 - Process flow for the materials used in this study to produce thin martensitic stainless steel strip for valves

3.2. Carbides

The microstructures of the starting material from both routes are shown in figure 3, namely 1mm cold rolled and annealed strip and 2.5mm cast and annealed strip respectively. Primary carbides were observed, at the center point of the thickness, in the cold rolled strip from the conventional route. The primary carbides detected were up to 5 μ m in size. The slab center is the location that exhibits the longest solidification time, during casting. It is therefore the last area of the slab cross section to solidify before the material leaves the continuous casting machine. Primary carbides are always formed in this area, as segregation takes place here during solidification. In the strip casting material, primary carbides were not only found in the center of the strip, but also between the dendrites. These formations are aligned diagonally to the longitudinal direction, i.e. along the direction of casting. The primary carbides of the strip cast material have a diameter below 1 μ m and thus are much smaller than those found in cold rolled strip from the conventional route. Furthermore, the size of the primary and secondary carbides within the strip cast material are similar. Under light microscopy, these could only be differentiated by their location in the material.

3.3. Surface defects

At the Zapp Precision Metals production plant in Germany, all incoming coil material (independent of production route) undergoes 100% automatic surface inspection. In the diagrams, shown in figure 4, the frequency of surface defects for both the conventional and the strip casting routes are compared for all stainless steel grades processed at this facility. The strip cast material is, in all cases, free of lamination type surface defects. This is likely because the reheating and hot rolling processes, during which such defects often occur, are not required with this route. Experience has shown that the strip casting process produces starting material, with an improved surface quality, for highly demanding applications.

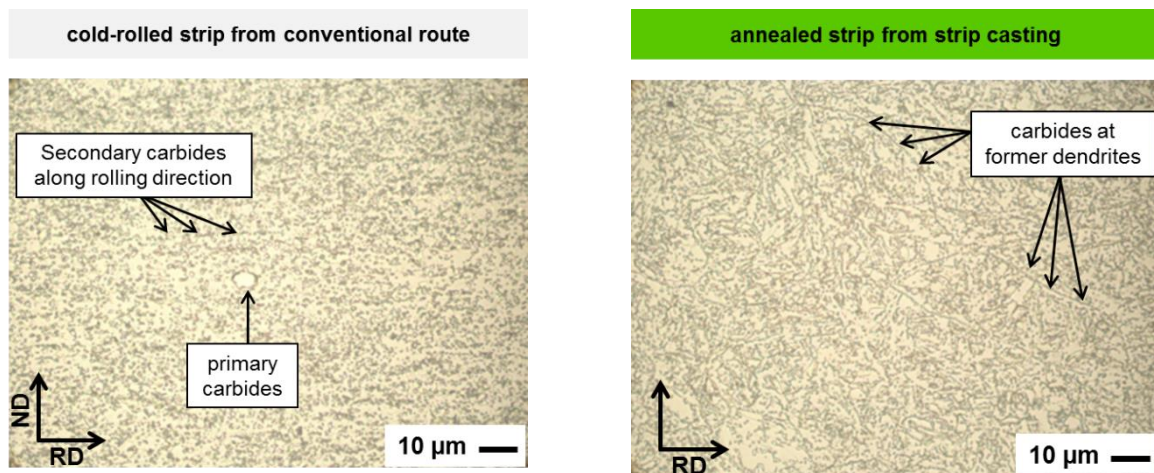


Figure 3 - Microstructure of 1mm thick cold rolled strip from conventional route (left) and annealed strip from the strip casting route (right), both after etching.

3.4. Thickness profile or crown

The thickness profile of the strip cast material was compared with that of the conventional route. The conicity, measured as the difference between the thickest and thinnest point divided by the width, was similar for the two routes.

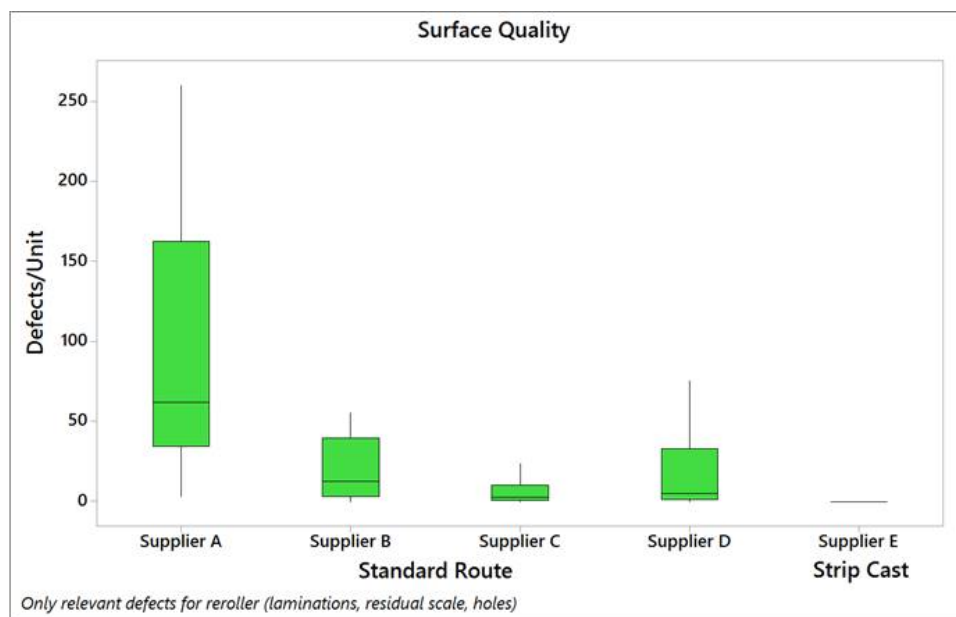


Figure 4 - Comparison of the surface quality, indicated as number of the defects, with root causes in the casting or hot rolling processes

Table 3 - Tensile properties of conventional route and strip casting material for hardened and tempered Zapp 1.4028MO

	tensile yield strength (MPa)	ultimate tensile strength (MPa)	elongation (%)
specification limits	1350 to 1550	1700 to 1900	≥ 5
conventional	1481	1841	5.8
strip casting	1488	1832	5.7

4. Comparison of final product from both routes for thin valves

4.1. Tensile properties

Comparable tensile properties were achieved using the same heat treatment parameters, i.e. standard hardening and tempering parameters used for Zapp 1.4028MO. The results are shown in table 3. The values for the conventional route are averages, calculated from serial production at Zapp in 2018.

4.2. Bending fatigue

In figure 5 the endurance limit determined using 3-point bending test is compared for both routes. The endurance limit was slightly higher for the strip cast material. The increase arises due to the smaller size of non-metallic inclusions and the reduced size of the largest secondary carbides.

4.3. Microstructure after hardening and tempering

Scanning electron microscopy was used to compare the secondary carbide size and distribution. Some exemplary micrographs are shown, for both routes, in figure 6. The results of the automatic quantitative microstructure analysis, as seen in table 4, show that the average diameter of carbides found in the strip casting samples was slightly larger than that of the conventional route (0.36 μm and 0.33 μm respectively).

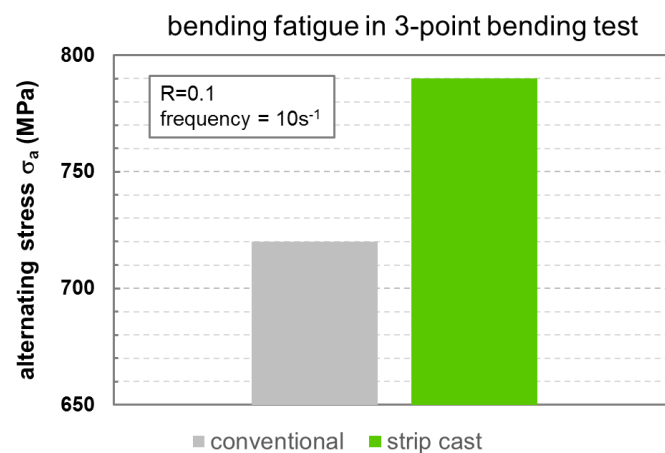
**Figure 5** - S/N curve measured in 3-point bending mode

Figure 7 shows, however, that the overall size range of secondary carbides is smaller for the strip casting product. Secondary carbides larger than $1.1\mu\text{m}$ were not found in the strip cast product. The number of secondary carbides found in the scanned area was smaller for the strip cast product and the absolute area was also slightly smaller. Because secondary carbides are brittle, and can result in local stress increases, they can represent possible sources of crack initiation during dynamic loading. The larger the size of these particles, the lower the endurance limit. The electron back-scatter diffraction technique was used to compare the martensitic microstructure of both routes. No discernible differences were observed, with respect to the effective grain size, lath width or phase fractions. In figure 8 examples of grain boundary maps for both sample sets are shown.

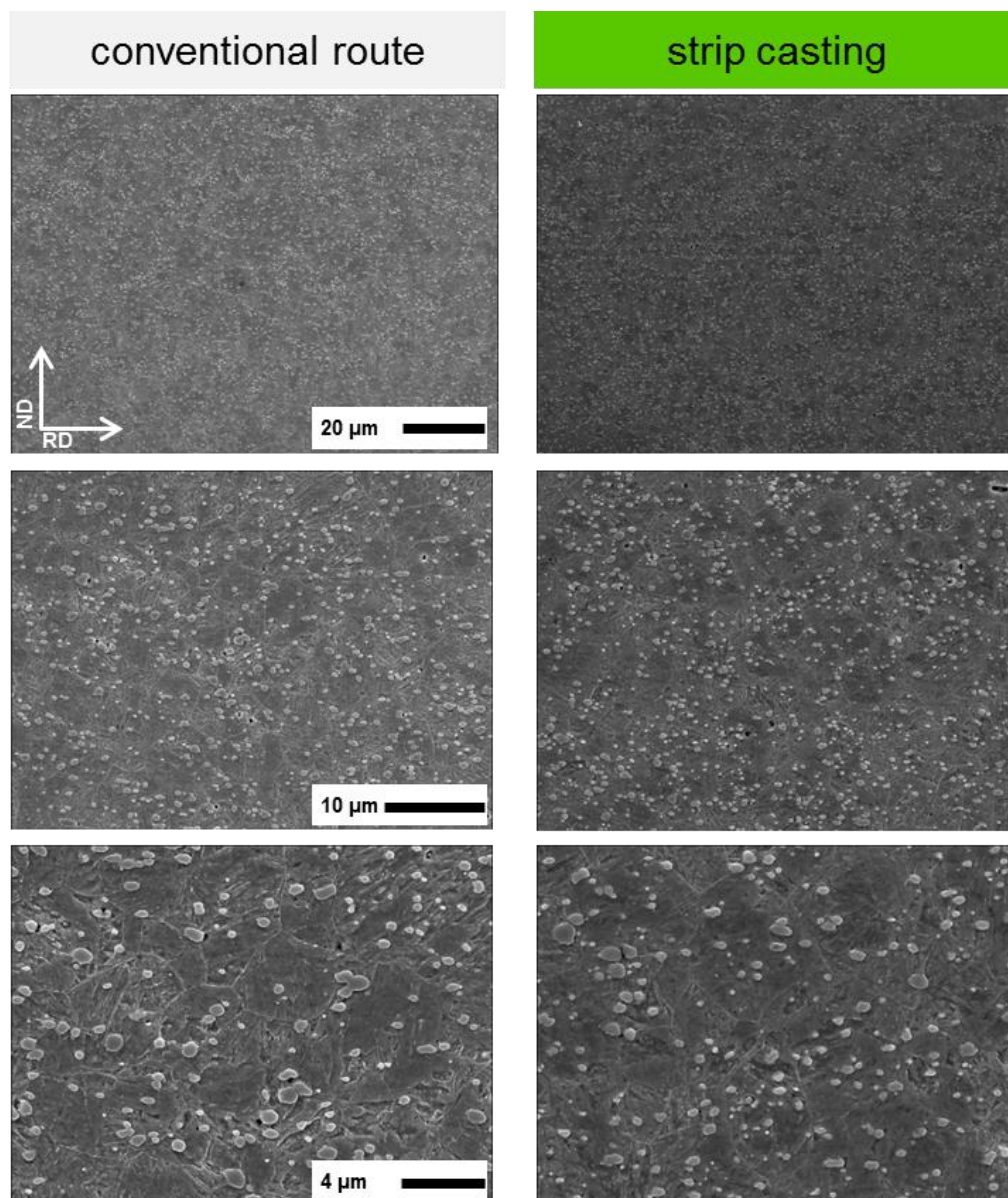


Figure 6 – Microstructure of hardened and tempered *Zapp 1.4028MO* produced from conventional route (left) and strip casting route (right), both after etching. Scanning electron microscopy performed on final product with a thickness of 0.15mm

Table 4 - Results of quantitative microstructure analysis of secondary carbides after hardening and tempering

	average diameter (μm)	standard deviation (μm)	number of secondary carbides
conventional	0.33	0.198	15795
strip casting	0.36	0.176	14072

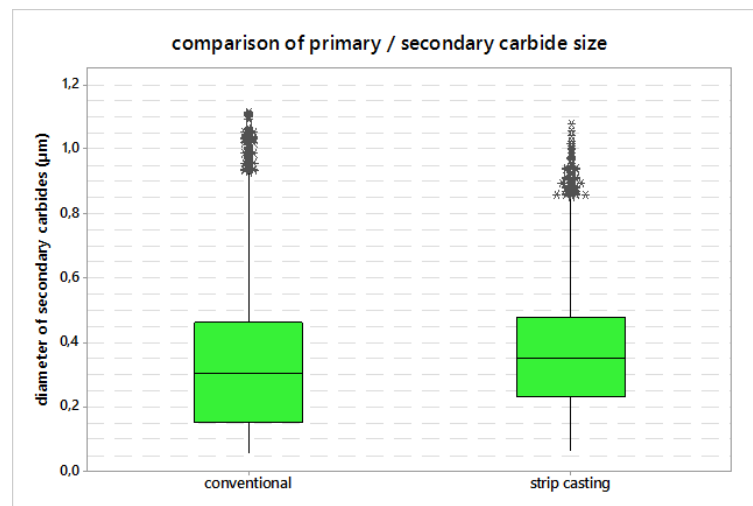
5. Conclusions

In this study martensitic stainless steel, produced by strip casting, was used for the first time to produce precision strip for flapper valves.

The main benefits of this new production route were found to be: -

- Absence of larger primary carbides, normally observed in traditional casting methods such as ingot or continuous slab casting,
- Smaller non-metallic inclusion size, allowing for use in higher demanding or thinner products,
- Reduced number of surface defects, resulting from hot rolling processes,
- Lower overall energy consumption in the production of strip, contributing to a reduced carbon dioxide emissions.

Finally, it was shown that while the same tensile strength properties as the conventional route were attained, the endurance limit of the strip cast material was slightly higher.

**Figure 7** - Comparison of the carbide diameter for conventional and strip casting route

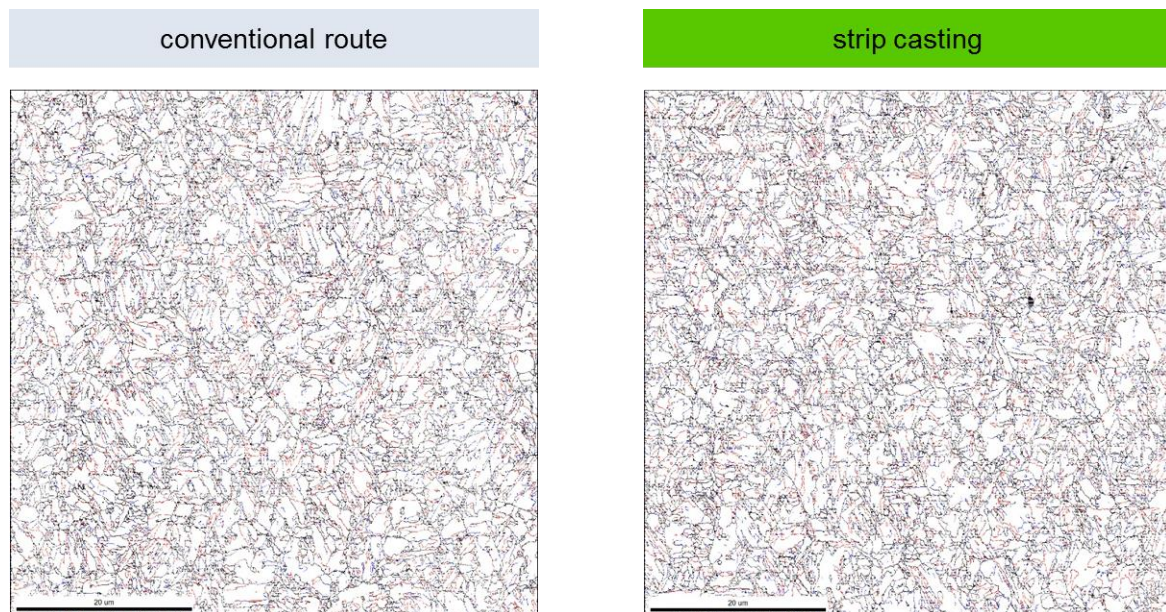


Figure 8 - Grain boundary maps of hardened and tempered strips from both casting routes. Black line: high angle grain boundary (15 to 62.8°); blue line: low angle grain boundaries (3 to 15°); red line: sigma 3 grain boundary with a tolerance of 8.7°

Acknowledgement

The EBSD investigations are carried out at the Salzgitter Mannesmann Research Center in Duisburg. The authors are grateful to Mr. Matthias Frommert and his colleagues for conduct these.

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